Enhanced Ocean Predictability Through Optimal Observing Strategies

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LONG-TERM GOALS

The primary long-term goal of our research is to develop optimal deployment strategies for drifter releases using templates derived from dynamical systems theory and to apply these to operational scenarios. The second goal is to improve current understanding of basic mesoscale and submesoscale oceanic processes. Both goals contribute to improved predictive capability of the marine environment. This research effort was initiated as a component of the DRI, *Predictability of the Ocean and Atmosphere*, and has contributed to the goals of that program by developing effective observation strategies for improved now-casts and forecasts of oceanic conditions.

OBJECTIVES

Three objectives were identified as important to achieving our long-term goals. First, integrate Lagrangian methods developed from dynamical systems theory into oceanographic applications. Second, use these methods to design optimal observing strategies with special emphasis on drifter deployments that achieve the maximum geographic coverage with the fewest units. Finally, apply the methodology to operational situations, specifically applications to data assimilating ocean models.

APPROACH

The technical approach taken in this project builds on results obtained by the PI from prior ONR support as well as collaboration with investigators at other institutions. The approach has three basic components. The first is to objectively reconstruct Eulerian velocities either from data assimilating models or from synoptic current maps in a format that can be used for the Lagrangian analysis. Here we have adapted methods initiated by Rao and Schwab (1981) and used by Eremeev et al. (1992a,b) and Lipphardt et al. (2000) as well as others for rendering these velocity fields. The second part is to calculate the critical material curves from the velocity archives by Lagrangian analysis. Our approach is adapted from that used by Miller et al. (1997) and Poje and Haller (1999). Since then a number of new developments have occurred that may improve this approach in future applications. See Boffetta et al. (2001), Haller (2001), Lapeyre et al. (2001), and Mancho et al. (2003) for examples. In this phase of the DRI we worked with Professors A. C. Poje, C.K.R.T. Jones, and Dr. L. Kuznetsov. Results from that collaboration are documented in Toner et al. (2001a), Poje et al. (2002), and Kuznetsov et al. (2002). For applications of Lagrangian analysis methods to data assimilating models

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we have developed a productive collaboration with Professor L. Kantha who maintains a state of the art data assimilating version of the Princeton Ocean model that has been adapted to many parts of the World Ocean. See Toner et al. (2001b), Kuznetsov et al. (2002), and citations in Publications.

WORK COMPLETED

As this is the fifth and final year of this DRI it is appropriate to summarize briefly the complete spectrum of work. In FY 99 we addressed several practical issues in the reconstruction of Eulerian velocity fields from Lagrangian data. The most significant development was specification of metrics for the accuracy of the reconstruction. This work was documented in Toner et al. (2001a). In FY 2000 we assessed the impact of including drifter data to enhance the velocity field from a state of the art data-assimilating model of the Gulf of Mexico and also showed how a simple predictive scheme could reliably predict trajectories up to a week. This was detailed in Toner et al. (2001b). We also analyzed output from this model using both dynamical systems templates, Kuznetsov et al. (2002), and traditional objective mapping methods, Toner et al. (2001b). During the third year (FY 2001) an optimal deployment strategy was applied to a double gyre model. As shown in Poje et al. (2002) the strategy based on dynamical systems concepts provided the best drifter dispersal and consequent reconstruction of the Eulerian velocity field.

During this fiscal year we have concentrated on two tasks. The first was to extend the optimal deployment strategies used in the double gyre model to realistic oceanic conditions. For this we used the data-assimilating model and compared predictions with the Littoral Warfare Advanced Development (LWAD) 98-2 Sea Test where an array of drifters was actually released in the Gulf. The model predicted the deployment pattern from the deployment in every detail. An informal report was provided to ONR management, which was used in presentations to support a new DRI. The second task was to use statistical methodologies to assess the predictability of the optimal deployment strategy. The original idea was to use ensemble methods for this analysis. However, a number of unexpected technical issues associated with the critical trajectories arose that required us to address their statistical properties before ensemble methods could be applied systematically. That work went exceptionally well and the results have been accepted for publication, see Toner and Poje (2003) under Publications.

RESULTS

The singular technical development during this FY was the demonstration that critical trajectories (hereafter hyperbolic trajectories) and associated inflowing and outflowing material curves really exist in the ocean. Previously we regarded hyperbolic trajectories as convenient abstractions that could be detected in simple dynamical models and postulated to exist in data assimilating models, but not corroborated by independent data. Two data sources now confirm their existence. The first was the outbreak of chlorophyll plumes across the Loop Current from the Yucatan to West Florida shelves, which was reported in last year's annual report and in Toner et al. (2003), see Publications below. The latest was the movement of the drifters deployed in the LWAD experiment.

Figure 1 below demonstrates the importance of the hyperbolic trajectories for the LWAD experiment.

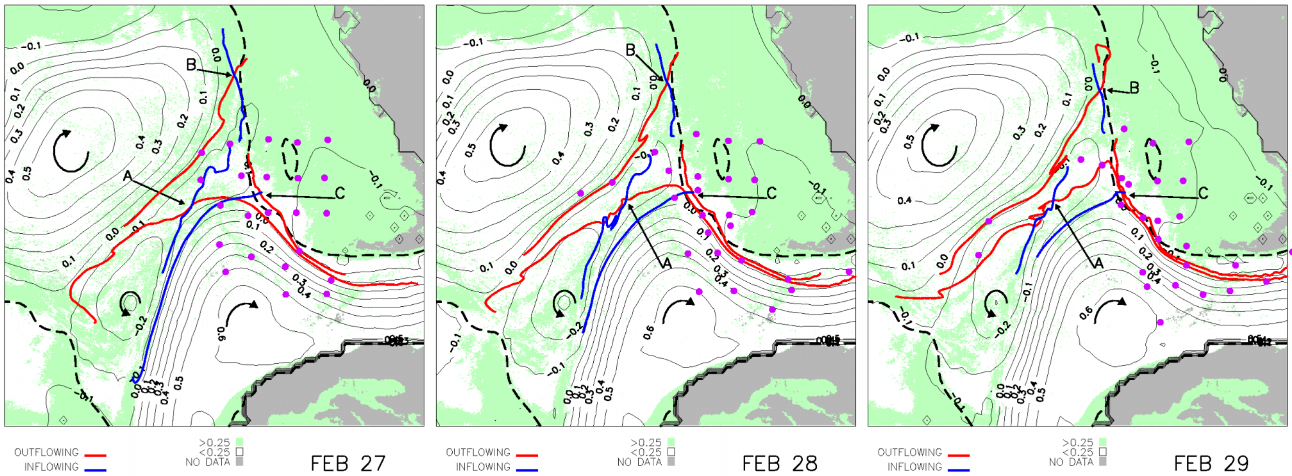

Figure 1. Hyperbolic trajectories (A, B, C) for three days during the LWAD 98-2 Sea Test. The red (blue) curves are their associated outflowing (inflowing) material curves.

This experiment took place off the southwest coast of Florida, which is shown as dark gray in the northeastern corner of the panels. Cuba is the dark gray figure in the southeast. The contour lines are the surface height anomaly in meters and the dashed line is the 110 depth contour. The drifter positions in each of the panels are shown as pink dots. February 27 is the second day of the launch. The eastern limb of the outflowing material curve from A forms a barrier that prevents drifters south of this from entering the shelf region. These drifters will either leave the Gulf of Mexico or migrate across the Loop Current and get trapped in the anticyclone off the coast of Cuba. The southern limb of the outflowing material curve from C forms a barrier for drifters deployed on the shelf. They are constrained to stay there unless they are located very near this curve. In that case they will be attracted to this outflowing material curve and leave the Gulf. The southwestern limb of the outflowing material curve from B and the northeastern inflowing curve to A form a channel in which three drifters flow southeast away from the deployment site. On February 27 one of these is located at the very end of the inflowing curve to A. The remaining drifters are kept in the deployment area by the outflowing curves from A and C.

Figure 2 focuses on two drifters the region in the vicinity of hyperbolic trajectory A for the period March 3-8. They both were deployed on the same height anomaly contour and the one just to the northwest of A was the drifter in the first panel of figure 1 that was at the edge of the northeastern limb of the inflowing material curve to A. This drifter was entrained in an intense mixing zone southwest of A while the other two drifters pulled off in this region moved into central part of the Gulf. This mixing zone is formed by the interaction of the inflowing material curve of a new hyperbolic trajectory off the Yucatan shelf. This is denoted as B in this figure and is not the same hyperbolic trajectory B in figure 1. The strong deformation around A and the proximity of B cause the material curves to foliate. Although the two drifters in this figure started on the same height anomaly contour they have completely different fates. The one to the northeast was kept in the deployment region by the material curves from A and B as described above.

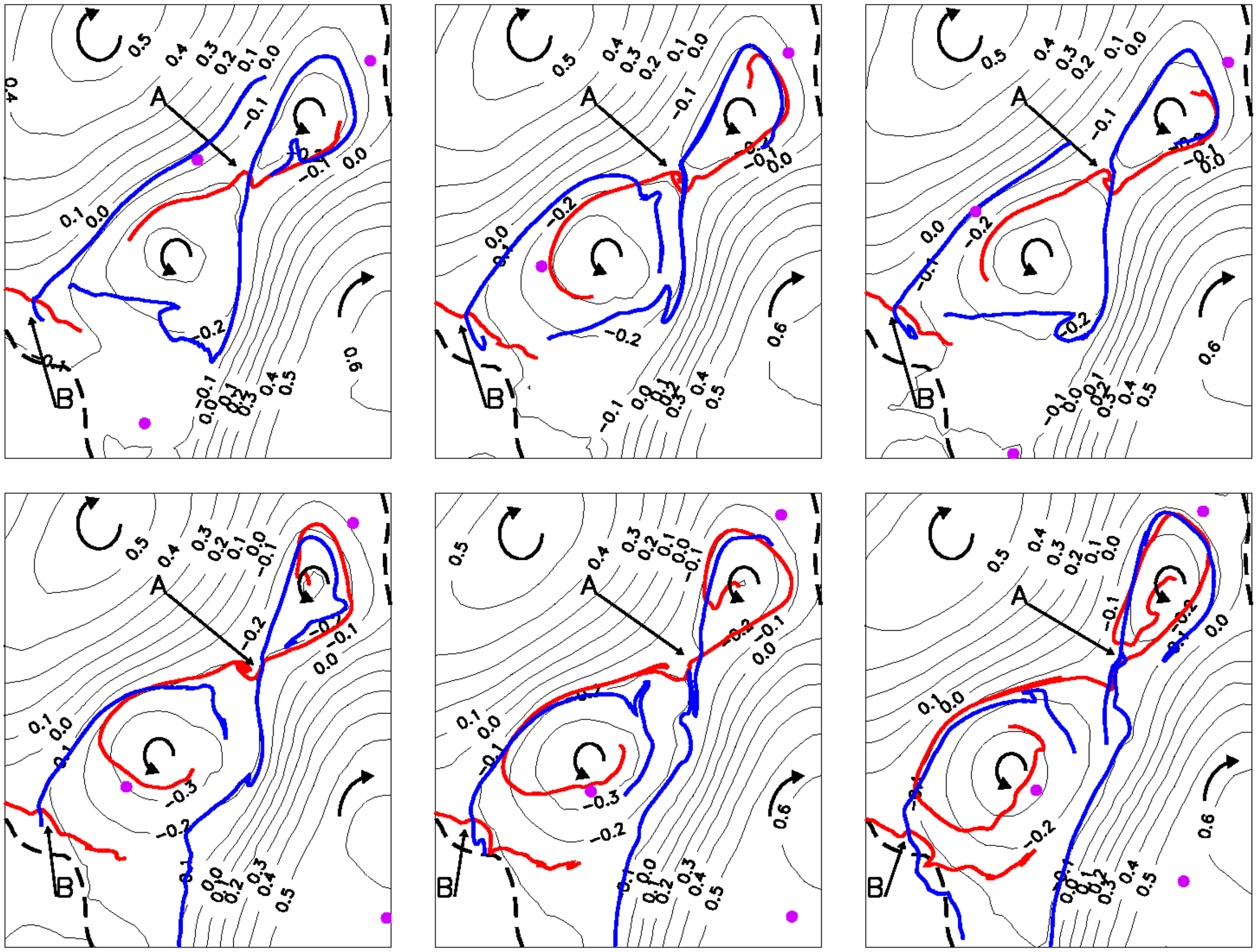

Figure 2. The behavior of two drifters deployed on the same height anomaly contour near hyperbolic trajectory A identified in figure 1.

What is the significance of hyperbolic trajectories and their associated material curves? First, it may be surprising to some that hyperbolic trajectories are found in regions of very low velocity, but extraordinarily high fluid stretch and deformation. Usually these regions are thought to be unimportant in prediction. Second, they are directly associated with the forecast and hindcast fields from data assimilating models. The inflowing material curves (blue in the figures) require future or predicted hydrodynamic fields, while the outflowing curves (red in the figures) depend on prior information. Thus calculations of these structures from the forecast and hindcast fields with subsequent verification from Lagrangian data provide a new and precise tool for model assessment. Third, the material curves parse the field into geographic regions that characterize the origin and fate of all the particles, without having to calculate this for every particle. In the LWAD experiment, for example, knowledge of the hyperbolic trajectories and their associated material curves would have been sufficient to have altered the deployment plan so that all the drifters would have stayed on the shelf. Finally these curves have conclusively demonstrated that traditional means of characterizing rings and eddies such as snapshots of closed isolines of geopotential or potential vorticity are not effective. The reason is that the Lagrangian time scale is much larger than the Eulerian time scale.

Hence flow in the vicinity of strong mesoscale structures is quite variable and there is far more small-scale advective exchange between the eddies and their environments than would be expected from an analysis of just Eulerian data. In such time dependent situations particles will cross isolines of stream function or vorticity over surprisingly short time scales particles. On the other hand the inflowing and outflowing material curves automatically account for the inherent variability in the flow field and thus effectively delineate the boundaries of coherent structures.

IMPACT

We expect this research will have a significant long-range impact on prediction of the marine environment. Substantial Lagrangian data are being generated for both scientific and operational use. But these data presently are neither being used for model validation nor assimilation into forecast models. The Lagrangian templates developed in this study produce very precise results that are amenable to tests through directed predictability experiments. The results produced for the LWAD experiment are perhaps the first example of how Lagrangian methods can be used for model evaluation. As oceanographers and modelers become familiar with Lagrangian data and analyses there will be motivation to include Lagrangian data in data assimilation.

This research is changing the way oceanographers view dynamical processes and stirring associated with coherent features such as rings and eddies. The Lagrangian methods developed in this study provide new insights into oceanic processes not readily seen in traditional Eulerian analyses.

TRANSITIONS

The templates developed in this study for optimal deployment of drifters are documented in Poje et al. (2002) and the report on the LWAD experiment is in the process of being adopted by NAVO for some operational situations. The CO-PI, Dr. M. Toner, is leaving the University of Delaware to take a position there to spearhead this effort.

RELATED PROJECTS

This DRI brought together scientists with a spectrum of capabilities to focus on aspects of prediction of the marine environment. During this past performance period Professor A. C. Poje at CUNY has collaborated on the development and application of dynamical systems templates and Professor L. Kantha of the University of Colorado has collaborated by providing simulations from a data assimilating general circulation model for realistic applications of the dynamical systems theory. There is also substantial collaboration with ONR project N0001400010067 that assesses Lagrangian transport determined from synoptic current observations obtained from high frequency radar. Here we interact with Dr. B. Lipphardt of the University of Delaware, Professor S. Wiggins of the University of Bristol (UK), and Professor J. Paduan of Naval Postgraduate School.

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